Using acoustic data from fishing vessels to estimate walleye pollock (*Theragra chalcogramma*) abundance in the eastern Bering Sea

Taina Honkalehto, Patrick H. Ressler, Richard H. Towler, and Christopher D. Wilson

Abstract: Eastern Bering Sea walleye pollock (*Theragra chalcogramma*) support one of the world's largest fisheries. Because of walleye pollock's high recruitment variability and relatively short life span, timely and accurate abundance indices are needed for fisheries management. Walleye pollock are surveyed biennially with an acoustic-trawl (AT) survey and annually with a bottom trawl (BT) survey. The latter tracks the demersal portion of the population using chartered fishing vessels, whereas the AT survey tracks the younger, midwater portion using research vessels and is critical for evaluating prerecruit abundances. Acoustic data collected from commercial fishing vessels conducting the BT survey were analyzed to provide information on midwater walleye pollock abundance at relatively low cost. A retrospective analysis of AT survey data identified a suitable index area to track midwater walleye pollock abundance. The BT survey acoustic data in that area tracked the AT survey abundance and captured its broad spatial patterns. This study is unique because commercial vessel acoustic data were used to estimate a new annual abundance index whose performance can be evaluated by a biennial research vessel survey. The new index will benefit managers by providing more accurate information on near-term abundance trends when dedicated research ship time is not available.

Résumé : Les goberges d'Alaska (*Theragra chalcogramma*) de la partie est de la mer Béring supportent une des plus grandes pêcheries du monde. A cause de la très grande variabilité du recrutement et de la durée de vie relativement courte de la goberge, des indices d'abondance précis et fait au moment opportun sont nécessaires pour la gestion de la pêcherie. La population de goberges d'Alaska est échantillonnée tous les deux ans par une campagne en mer couplant des inventaires acoustiques et du chalutage (AC), et annuellement par une campagne de chalutage de fond (C). Cette dernière estime la proportion démersale en utilisant des navires de pêche commerciale affrétés, alors que la campagne AC estime la proportion pélagique des individus plus jeunes en utilisant des navires de recherche. Les campagnes AC sont d'une importance critique pour l'évaluation de l'abondance des pré-recrues. Les donnés acoustiques collectées à bord des navires de pêche commerciale réalisant les campagnes C ont été analysées pour fournir des informations à coût relativement modique sur l'abondance des goberges d'Alaska pélagiques. Une analyse rétrospective des données de campagne AC a identifié une zone indicatrice appropriée pour suivre l'abondance des goberges d'Alaska pélagiques; les données acoustiques de la campagne C dans cette zone suivent les abondances des inventaires de la campagne AC et en capturentles patrons spatiaux généraux. Notre étude est unique, car les données acoustiques des navires commerciaux sont utilisées pour estimer un nouvel indice annuel d'abondance dont la performance peut être évaluée tous les deux ans par une campagne en mer d'un navire de recherche. Le nouvel indice bénéficiera aux gestionnaires en fournissant des informations plus précises sur les tendances d'abondance à court terme lorsque du temps spécialisé de navire de recherche n'est pas disponible.

[Traduit par la Rédaction]

Introduction

Walleye pollock (*Theragra chalcogramma*) is an abundant, semidemersal gadid fish that inhabits the continental shelf waters of the North Pacific Ocean from Washington State, USA, north and west to Japan. In the US Exclusive Economic Zone within the eastern Bering Sea (EBS), this species supports one of the world's largest commercial fisheries (Food and Agriculture Organization of the United Nations 2009). Since the late 1970s, walleye pollock have been monitored by two fishery-independent summer surveys conducted by scientists from the National Oceanic and Atmospheric Administration's (NOAA) Alaska Fisheries Science Center (AFSC). One survey is dedicated primarily to evaluating walleye pollock abundance and uses acoustic-trawl (AT) methods deployed from NOAA research vessels. This biennial survey is costly but valuable because it covers the generally younger, midwater component of the walleye pollock stock. The other survey is multispecies and provides an index of the older, demersal component of the walleye pollock population. This annual survey uses area-swept bottom trawl (BT) survey methods aboard chartered commercial fishing vessels. Both surveys are critical to the assessment and management of

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this stock (Ianelli et al. 2009). The walleye pollock population is highly variable and in recent years has declined following a period of below-average recruitment in 2001–2005, heightening the need for accurate and timely information on stock status (Ianelli et al. 2009). Annual acoustic data obtained from the commercial fishing vessels conducting the BT survey could provide an economic and timely way to augment the biennial fishery-independent data used to estimate the midwater component of the EBS walleye pollock stock.

Commercial fishing vessels have been used to collect acoustic data for fisheries research purposes where dedicated research vessels are not available. The use of these data from commercial fishing vessels has recently been reviewed (International Council for the Exploration of the Sea 2007) and remains an active area of research (e.g., Wyeth et al. 2000; Mackinson and van der Kooij 2006; Pena 2008). For example, acoustic data collected on commercial vessels during a fishing season have been used to estimate hoki (*Macruronus novaezelandiae*) biomass in New Zealand (O'Driscoll and Macaulay 2005) to characterize herring abundance indices in eastern Canada (Claytor and Allard 2001) and to examine commercial fishing effects on walleye pollock aggregations in the EBS (Barbeaux et al. 2005; Shen et al. 2009). Commercial vessel acoustic systems have also been used in directed studies to examine the behavioral response of fish to trawling vessels (De Robertis and Wilson 2006) and to study the effect of light intensity on walleye pollock availability to EBS AT and BT surveys (Kotwicki et al. 2009). Many commercial walleye pollock vessels in Alaska are equipped with Simrad ES60 echo sounders (Simrad, Kongsberg AS, Horten, Norway), which are capable of collecting and storing scientific quality acoustic data.

The goal of this project was to evaluate whether acoustic data collected aboard commercial fishing vessels during a BT survey could be used to create a reliable abundance index for the midwater portion of the walleye pollock stock, which was not targeted by this survey. The acoustic data were collected under methods quite different than those employed during dedicated AT surveys. For example, we had very limited control over the vessels used, the acoustic equipment used or frequency that the instruments were monitored during the cruise, and other day-to-day data collection operations. It was also not possible to directly sample the acoustic backscatter for species classification, nor run a trackline pattern recommended for a dedicated acoustic survey (Simmonds and MacLennan 2005). Nevertheless, the project was feasible because walleye pollock account for a large proportion of midwater backscatter in the EBS, the BT survey coverage was adequate, and the resulting index could provide data on a critical component of the walleye pollock population that would be otherwise unavailable during off-years for the AT survey.

Materials and methods

Surveys

The NOAA AT and BT walleye pollock stock assessment surveys take place in June and July, proceeding from east to west across the EBS shelf and slope during daylight hours (Fig. 1*a*). They cover regions between approximately the 50 and 1000 m isobaths (AT survey) and the 20 and 200 m isobaths (BT survey; Fig. 1*a*). The BT survey covers a larger total area than the AT survey to also monitor commercially important crab and other groundfish species. Methods for each survey are described briefly, as more detail is available elsewhere (Honkalehto et al. 2008; Lauth 2010).

The biennial AT survey is currently carried out aboard one of two NOAA research vessels (63–66 m in length) equipped with calibrated scientific echo sounders connected to split-beam transducers attached to a centerboard located 9 m below the water surface. The principal frequency used to survey walleye pollock is 38 kHz. Acoustic backscatter data were collected along parallel north–south transects spaced 37 km apart at a nominal vessel speed of 6.2 $m \cdot s^{-1}$ from about 14–16 m from the surface to within 0.5 m of the bottom, to maximum depths of 500 m. Midwater trawls are conducted to verify the species composition of the observed backscatter and to collect other biological information. Acoustic backscatter data are manually classified into taxonomic groups by trained analysts based on a visual examination of backscatter characteristics and on the species composition of midwater trawl catches. Walleye pollock length, mass, and age information from the trawls are then used to convert the echo integral data attributed to walleye pollock into numbers and mass of walleye pollock per unit area, which are expanded to represent the midwater component of the walleye pollock stock for the surveyed area. The demersal component of the walleye pollock stock is assessed by the BT survey as described below.

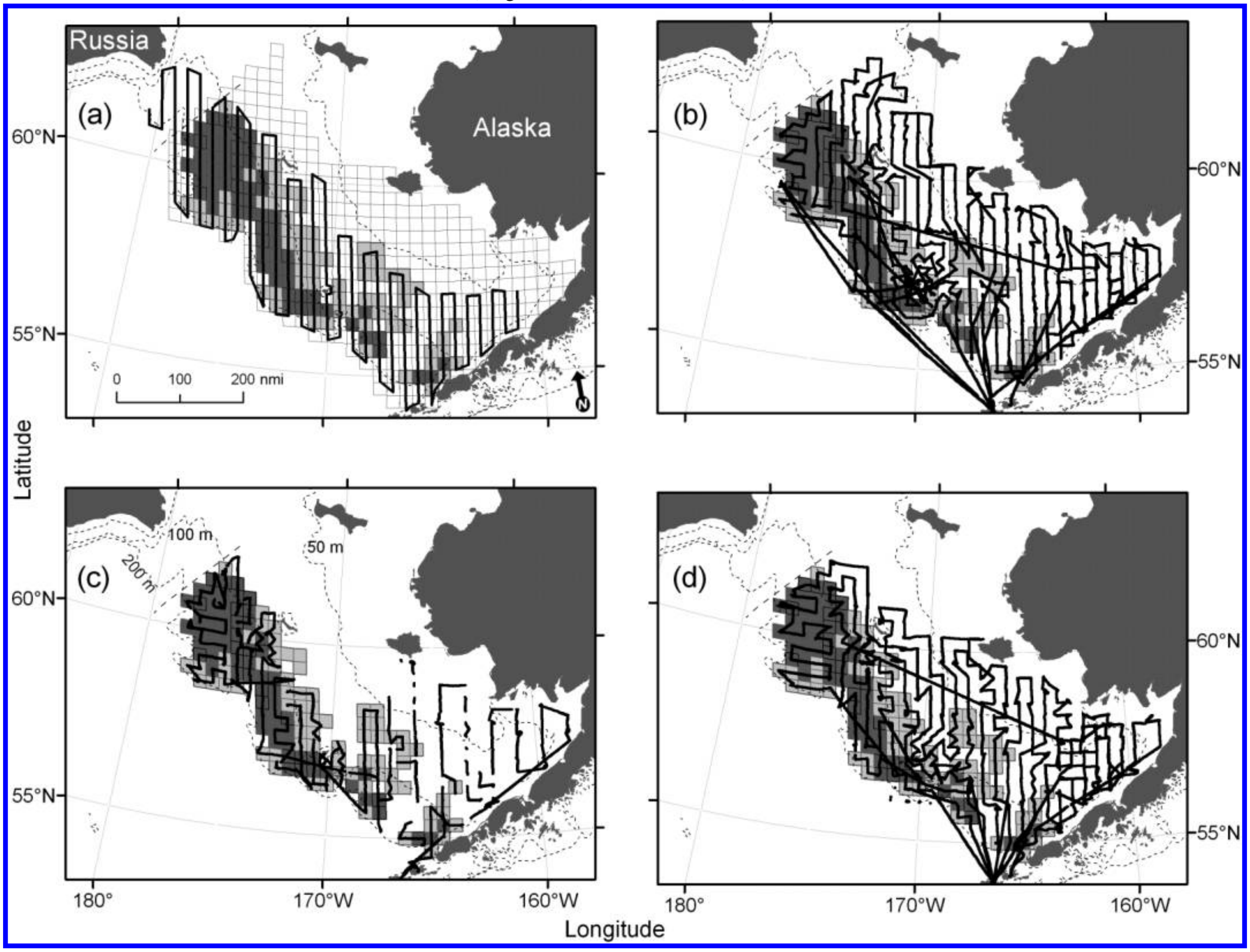
The annual BT survey is conducted aboard two chartered commercial fishing vessels (40–50 m in length) that deploy bottom trawls in a grid of 396 stations spaced 20 nautical miles (nmi) (37 km) apart, forming rows of 37 km × 37 km cells (Fig. 1*a*). About 280 cells overlap the AT survey trackline. Nominal vessel speeds range from about 1.5 $m \cdot s^{-1}$ when trawling to about 4.6–5.7 $m \cdot s^{-1}$ when free-running. The bottom trawl catch-per-unit effort for walleye pollock is used to estimate demersal biomass. BT survey vessels are typically equipped with commercial echo sounders and hull-mounted transducers located 4–5 m below the water surface.

Acoustic data collection and processing

Routine AT surveys were carried out in 2006–2009 using Simrad EK60 scientific echo sounders operating at 38 kHz and standard acoustic survey methods (Honkalehto et al. 2002, 2010). The Simrad acoustic systems were calibrated before, during, and after the surveys using standard sphere techniques (Foote et al. 1987).

Routine BT surveys were carried out in 2006–2009. For this project, acoustic data collected from the commercial vessels were required to be of higher quality than typically available from these platforms. Whereas on AT surveys acoustic data were collected, examined, and postprocessed in near real time by acoustics experts, on the chartered BT survey vessels large volumes of acoustic data were collected semi-automatically without immediate review by an acoustics expert. To obtain high-quality, midwater acoustic information, detailed protocols for data collection (International Council for the Exploration of the Sea 2007) and custom, semi-automated, data analysis software for postprocessing were developed. Collection of the acoustic data required close collaboration with BT survey vessel skippers and survey personnel regarding mutually acceptable data collection protocols and

Fig. 1. Study area showing (*a*) typical spatial coverage of the bottom trawl (BT) survey (squares) and acoustic-trawl (AT) survey (solid lines), (*b*) 2006 BT vessel tracks, (*c*) 2007 BT vessel track (only the vessel (one of two) that collected 38 kHz acoustic data is shown), and (*d*) 2008 BT vessel tracks. The 2009 vessel tracks (not shown) were very similar to 2006 and 2008. Shaded squares indicate index area cells where data were autoprocessed (dark gray) or hand-processed (medium gray). Also shown are depth contours (short dashes) and the boundary between the USA and the Russian Exclusive Economic Zone (long dashes). 1 nautical mile (nmi) = 1.852 km.



vessel logistics, in particular because acoustic data collection was not the primary BT survey objective. Common concerns affecting acoustic data quality included system installation issues; noise from various acoustic (other sounders, bubble sweepdown), electrical, or mechanical sources; intermittent navigation information; and inconsistent bottom tracking.

BT survey acoustic data were collected with Simrad ES60 commercial echo sounders and split-beam transducers operating at 38 kHz. Other acoustic devices aboard the vessels were either synchronized with the ES60 or turned off while data were collected to prevent interference. The Simrad acoustic systems were generally calibrated at the start and end of the surveys using standard sphere techniques (Foote et al. 1987); except for expediency, the vessels were drifting instead of anchored during the calibration. The standard target was suspended as close as possible to the main axis of the beam, and only detections close to the center of the beam (defined as a maximum applied beam compensation of $\leq$0.3 dB) were used to compute new gain values. Sound speed and absorption settings for processing BT survey acoustic data were based on prior EBS AT surveys. Upper and lower depth bounds for BT acoustic data collection were the same as those for the AT survey: from about 14–16 m from the surface to within 3 m of the bottom. A systematic ping-indexed bias present in ES60 raw data files was removed using either a Java utility (T. Ryan and R. Kloser, CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart 7001, Australia, personal communication, 2005) or a custom-written Matlab (The Mathworks, Natick, Massachusetts, USA) software program described below.

The hull-mounted transducers on BT survey vessels were more susceptible to the effects of air bubbles sweeping across the transducer face (bubble sweepdown) than the centerboard-mounted transducers on the AT survey vessel (Ona and Traynor 1990; Cox et al. 2006). These bubbles can cause attenuation of sound transmission and reception of echoes. Two simple data filters were developed to remove pings compromised by bubble sweepdown. For each ping in an ES60 raw data file, the transmit pulse S_v was tested for deviations greater than ±2% of the long-term mean from each BT survey, the same standard expected from experience with AT survey research vessel data. Pings exceeding this standard were removed. Also, a bottom echo filter removed pings having a weak bottom echo (mean $S_v < -40.0$ dB). As it was uncertain whether all pings compromised by bubble sweepdown were detected and removed by these filters, the filtered data files were used only if less than 15% of the pings in a raw file had been removed. Otherwise the entire data file was considered compromised and was excluded from further analysis.

Overall, the 2006 through 2009 field methods specific to the AT and BT surveys were similar across years, with slight variations in participating vessels and survey timing (Table 1; Figs. 1*b*, 1*c*, 1*d*; Honkalehto et al. 2010; Lauth 2010). Although two vessels were contracted to conduct the 2007 BT survey, only one was equipped with a 38 kHz echo sounder and used in this study.

To facilitate rapid processing of the large volumes of BT acoustic data, a customized postprocessing system called rawLoader was developed in MatLab. RawLoader was used to read Simrad ES60 (and ER60) .raw files, convert raw power and electrical angles, mask and filter data, apply calibration parameters, create analysis intervals (e.g., 0.5 nmi (0.93 km) elementary distance sampling units (EDSUs) along the vessel path and 10 m vertical depth bins), and perform echo integration. Additional features of rawLoader included automated removal of the systematic ping-indexed bias present in ES60 data, enhanced bottom detection, flagging of extreme high or low s_A (nautical area scattering coefficient ($m^2 \cdot nmi^{-2}$); MacLennan et al. 2002) value pings, and flexible ping filtering to remove most bubble sweepdown effects. Resulting echo integration information was stored in a relational database, and echogram image files were created to allow visual audits of the data. Echoview software (Myriax Pty., Ltd., Hobart, Tasmania, Australia) was used to analyze acoustic backscatter data where the presence of contaminant taxa required manual processing. As an initial quality control measure, rawLoader echogram images of all data were examined to detect large problems such as invalid bottom detections, acoustic interference, and non-walleye pollock backscatter.

Retrospective analysis

A retrospective analysis of AT survey data (1999–2004) was completed to explore ways to save time postprocessing the BT survey data. The analysis identified an index area on the EBS shelf where much of the acoustic backscatter at 38 kHz was attributed to walleye pollock. It also determined where the acoustic data could be automatically processed in the custom Matlab software or where the presence of substantial backscatter from other taxa required manual processing to identify and isolate walleye pollock backscatter. The suitability of the index area was assessed by testing the ability of its summed backscatter over a portion of the water column to track the AT survey walleye pollock biomass time series. Subsequently, the acoustic data inside the index area from the 2006–2009 BT surveys were used to generate a walleye pollock abundance index. This reduced the entire BT survey data set to a smaller geographic area, which expedited postprocessing and index computation.

The four most recent years of AT survey data available when this study began (1999, 2000, 2002, and 2004) were used for the retrospective analysis. These AT surveys were chosen because their start and end dates closely matched those of the bottom trawl surveys, and the methods used were most similar to current practices. All acoustic backscatter data (s_A) classified to taxonomic groups (e.g., walleye pollock, non-walleye pollock fish, near-surface fish – plankton mix) were stratified into 37 km × 37 km BT survey cells and reanalyzed as follows (Fig. 1*a*). First, cells were selected where AT survey walleye pollock backscatter was (*i*) present above a minimum level (≥100 s_A) and (*ii*) the predominant fraction of total backscatter (≥70% of total s_A) in at least 1 of the 4 years. These presence and predominance criteria were chosen based on observations of walleye pollock backscatter over the EBS AT survey time series. The 138 cells that passed these thresholds were combined into an index area covering a little more than half of the normal AT survey area (Fig. 1*a*, shaded cells). Second, to determine whether cells could be automatically processed or required manual processing, the number of survey years (1–4) when each index cell met both area thresholds was noted; based on this categorization, the index area was divided into two subareas. Cells where walleye pollock backscatter passed the present and predominant thresholds for more than one survey year comprised the first subarea (about half of the index area; Fig. 1*a*), and all backscatter in the water column between 30 m from the surface and 3 m above bottom was automatically attributed to walleye pollock. Backscatter shallower than 30 m was excluded, as it typically comprises a variable mixture of other fishes and plankton. Cells where walleye pollock backscatter met the minimum thresholds in only one survey year comprised the second subarea. Here, backscatter attributed to non-walleye pollock targets was common throughout the water column, and thus more careful, manual processing was required to classify backscatter as walleye pollock. Finally, walleye pollock backscatter from the two index subareas was combined, and a walleye pollock abundance index (I_{AT}) for each year was computed from the AT survey backscatter data in the index area as follows:

$$(1) \qquad I_{AT} = c\sum \overline{s}_{Aj}$$

where $\overline{s}_{Aj}$ is the average s_A attributed to walleye pollock from all 0.5 nmi (0.93 km) EDSUs in index area cell j ($m^2 \cdot nmi^{-2}$), c is cell area (= 400 nmi^2), and the summation is over all index area cells.

Two simple procedures were performed to validate the empirically chosen thresholds for walleye pollock backscatter presence (≥100 s_A) and predominance (≥70% of total backscatter) that were used to define the index area and to evaluate how much manual versus automatic classification of walleye pollock was necessary in the retrospective analysis. First, higher and lower threshold combinations were systematically chosen, and the index area and values were recomputed and compared with those produced with the original thresholds. In the second procedure, an index of undifferentiated backscatter (I_{UDB}) was computed in the same way as I_{AT} (eq. 1), except that all AT survey backscatter between 30 m from the surface and 3 m off bottom in the entire index area was attributed to walleye pollock. The I_{UDB} (1999–2004) simulated the effect of automatically processing all index area data to test whether all data below 30 m could be classified

Table 1. Dates and vessels used for the Alaska Fisheries Science Center acoustic-trawl (AT) and bottom trawl (BT) stock assessment surveys during summer 2006–2009.

	BT surveys		AT surveys	
Year	Charter vessel (length)	Survey dates	NOAA vessel (length)	Survey dates
2006	*Arcturus* (40 m), *Northwest Explorer* (49 m)	30 May – 28 July	*Miller Freeman* (66 m)	3 June – 25 July
2007	*Arcturus*	4 June – 2 August	*Oscar Dyson* (63 m)	2 June – 30 July
2008	*Arcturus*, *Aldebaran* (40 m)	2 June – 26 July	*Oscar Dyson*	2 June – 31 July
2009	*Arcturus, Aldebaran*	28 May – 31 July	*Oscar Dyson*	9 June – 7 August

as walleye pollock, which would dramatically shorten the processing time needed to produce an index.

BT survey index and index–survey comparisons

Between 2006 and 2009, a BT survey index (I_{BT}) was computed in the same way as I_{AT} (eq. 1), except using BT survey acoustic data. Following AT survey procedures for assessing walleye pollock, we used only BT survey data that were collected during daylight hours and when the vessels were not trawling (defined as vessel speeds > 2.1 m·s^{-1}). The maximum depth limit for analysis was set at 200 m, roughly the outer Bering Sea shelf break. In each of those years, for reasons not connected to this study, annual summer AT surveys were conducted as opposed to the usual biennial schedule. This allowed us to compare the AT survey biomass with I_{BT} to validate the new abundance index. For the comparison, the AT survey biomass was normalized to mean 1999–2004 values, and the I_{BT} time series was normalized to the mean I_{AT} values from 1999–2004, as there were no BT survey data from those years. The trend in each time series was compared to assess whether I_{BT} tracked the AT survey biomass and could therefore be used to increase the number of walleye pollock stock abundance observations at a low additional cost.

Spatial statistics (Bez et al. 1997; Woillez et al. 2007, 2009) were computed to compare the distribution patterns and degree of overlap and coherence between walleye pollock backscatter from the AT survey and I_{BT}. The spatial indices included center of gravity (CG) and corresponding inertia, as well as global and local indices of spatial collocation (I_{g} and I_{l}; Bez and Rivoirard 2000; Petitgas et al. 2009). The global index of collocation is computed from CG and inertia and measures the large-scale overlap of two distributions with values ranging from 0 (no overlap) to 1 (complete overlap). The local index of collocation measures the fine-scale spatial coherence, with values ranging from 0 (no coherence) to 1 (complete coherence). Each data set was averaged into the same set of 37 km × 37 km BT survey cells (Fig. 1*a*) prior to computation of spatial statistics. Finally, the percentage of AT survey walleye pollock biomass in the index area each year was computed to gauge whether the index area developed in the retrospective analysis captured the spatial extent of most EBS walleye pollock.

Relative estimation errors associated with acoustic data sampling variability and spatial structure were derived for index and survey totals in each year using a one-dimensional geostatistical method (Petitgas 1993; Rivoirard et al. 2000; Walline 2007). North–south columns of BT grid cells were treated as transects for the purpose of the computations. Relative estimation error is defined as the ratio of the square root of the geostatistical estimation variance to the summed biomass or acoustic backscatter (Rivoirard et al. 2000). The relative estimation errors were multiplied by 1.96 to approximate 95% confidence intervals about each survey sum, assuming errors were normally distributed. This procedure is reasonable; Walline (2007) used conditional geostatistical simulations to show that biomass estimates from Bering Sea walleye pollock surveys were approximately normally distributed and furthermore that confidence intervals computed as twice the one-dimensional relative estimation error were very similar to 95% confidence intervals estimated from the probability distribution function of survey estimates derived from many simulations.

Results

Calibration and data quality

The acoustic system calibrations for all vessels in each year indicated that instrument performance was acceptable and that there were no large changes in sensitivity in the acoustic systems during the surveys (Fig. 2). This allowed for unbiased comparison in acoustic backscatter trends. The variability in S_v gain for BT survey vessels was generally similar to that for the AT survey vessels. The wider variation between calibrations for *Arcturus* in 2007 was likely due to poor conditions experienced during the calibrations when the vessel was in open water rather than being sheltered inside a bay as was more typical.

The centerboard-mounted transducers on the AT survey vessels were not noticeably affected by bubble sweepdown, but the hull-mounted transducers on the BT survey vessels were affected, particularly in rough sea conditions or high vessel speeds. Using the transmit pulse and bottom data filters on BT survey data sets removed, on average, about 7% of the 0.5 nmi (0.93 km) EDSUs (Table 2). The greatest percentage of interval removals occurred in 2007 (17.2%). This was likely because *Arcturus*' mean transit speed in 2007 was about 0.4 m·s^{-1} higher than in other years, which potentially exacerbated bubble sweepdown effects. The increased speeds occurred because *Arcturus* covered extra trackline to sample index area cells that were surveyed by the second (non-38 kHz) vessel. Higher percent removals were also correlated with adverse weather conditions. In 2006, *Northwest Explorer* experienced some relatively rough sea states and bad weather conditions, while *Arcturus* surveyed elsewhere. In 2009, sea state conditions were generally worse throughout the summer than in the other years. As pings affected by bubble sweepdown have very low s_A, their presence negatively biased the water column backscatter data, decreasing the total measured s_A, and their removal resulted in a proportional increase in s_A for these data sets.

Table 2. Percent removal of 0.5 nmi (0.93 km) elementary distance sampling units (EDSUs) where ≥15% of pings failed the transmit pulse and bottom ping filters, by vessel and year.

	2006		2007	2008		2009		
	Arcturus	*Northwest Explorer*	*Arcturus*	*Arcturus*	*Aldebaran*	*Arcturus*	*Aldebaran*	2006–2009 mean
% intervals removed because of ≥15% pings failing filters	3.71	9.07	17.23	1.09	2.63	10.19	7.17	7.30
Mean vessel speed ($m \cdot s^{-1}$)	4.76	4.90	5.21	4.88	4.62	4.57	4.29	4.75
Total number of 0.5 nmi EDSUs	2968	4962	5822	2756	4140	4181	4127	4137

Note: Vessel speeds were >2.1 $m \cdot s^{-1}$.

Fig. 2. Integration gain (i.e., S_v gain) measured in standard sphere calibrations normalized to the mean value for each vessel–year combination during the summer 2006–2009 eastern Bering Sea acoustic-trawl and bottom trawl surveys. System settings for data processing were as follows: frequency 38 kHz, sound speed 1470 $m \cdot s^{-1}$, absorption 0.01 $dB \cdot m^{-1}$, pulse length 1.024 ms, and power 2000 W. Two-way beam angle was –20.6 dB for *Aldebaran*, *Arcturus*, and *Northwest Explorer*. Two-way beam angle for *Miller Freeman* was –21.0 dB and for *Oscar Dyson*, –20.7 dB.

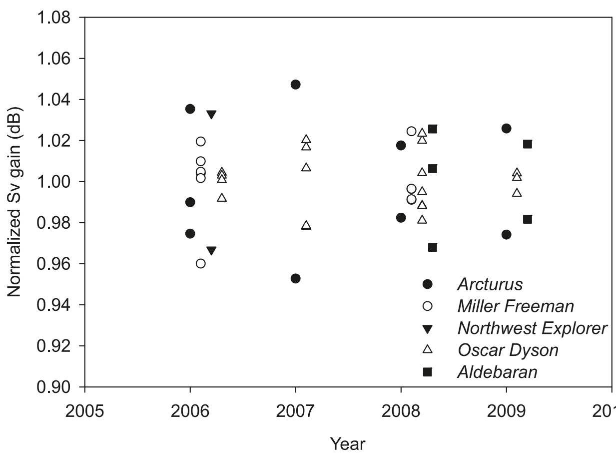
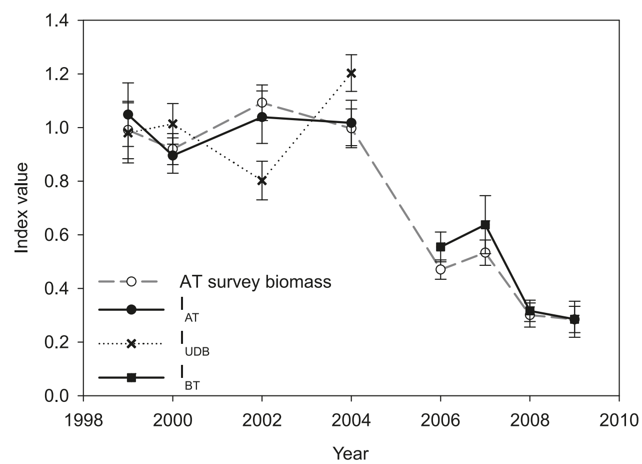


Fig. 3. Time series of acoustic-trawl (AT) survey biomass and I_{AT}, I_{UDB}, and I_{BT} indices. Each time series was divided by its average during the period 1999–2004. Error bars indicate 1D geostatistical 95% confidence intervals.



Retrospective analysis (1999–2004)

The I_{AT} closely tracked the temporal pattern in AT survey walleye pollock biomass, in terms of magnitude and direction of changes relative to 2004, across all 4 years ($r^2 = 0.58$; Fig. 3). The 1D geostatistical error bars about the values in each time series indicate that I_{AT} has a similar relative estimation error (0.04–0.06) to that of the AT survey (0.03–0.06; see table 7 in Honkalehto et al. 2010).

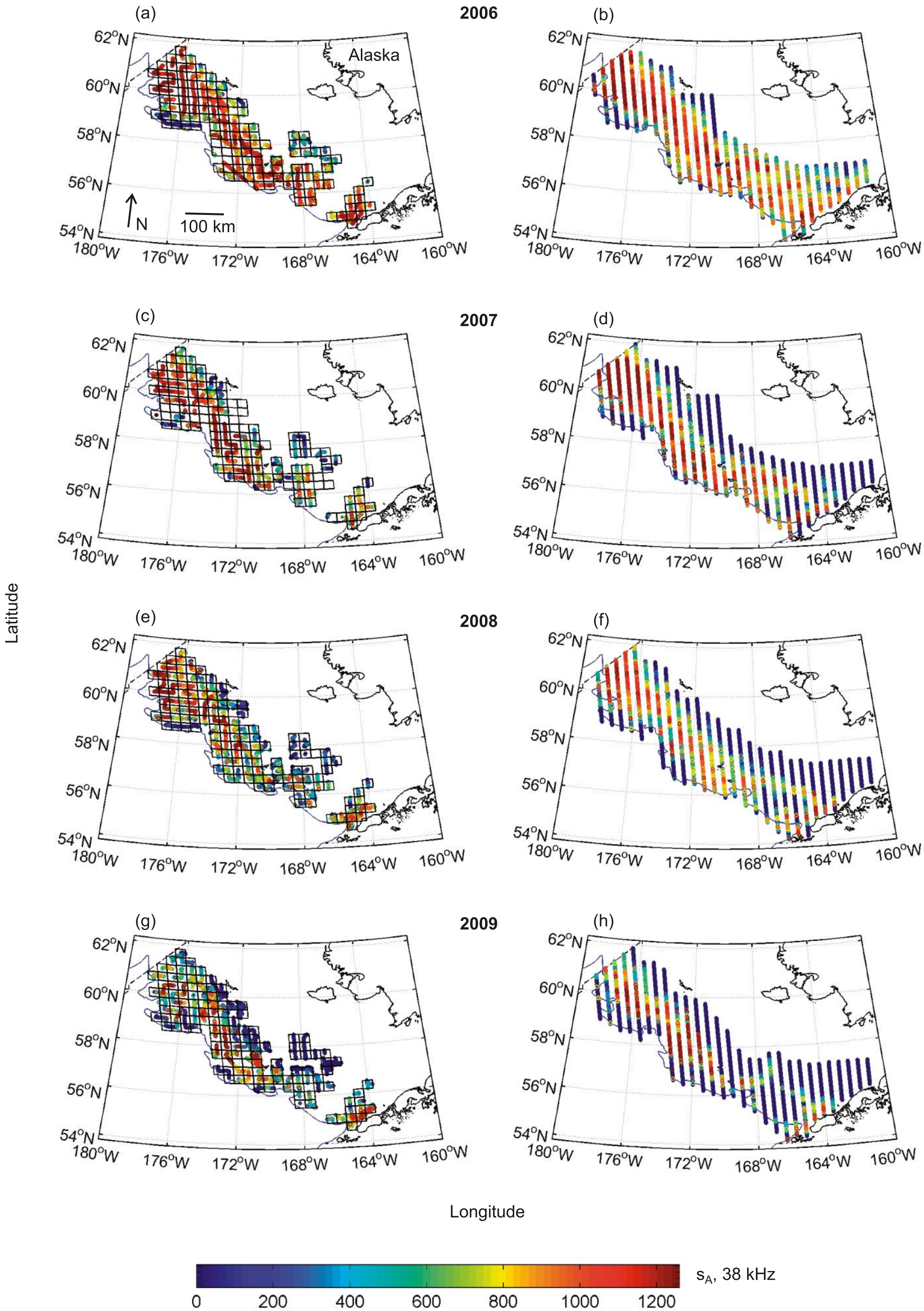
The simple procedures to evaluate the walleye pollock presence and predominance thresholds used to choose the cells of the index area indicated that using stricter criteria (e.g., requiring the minimum walleye pollock s_A to be more than 100 or the minimum total s_A attributed to walleye pollock to be more than 70% of total s_A) did not improve index performance, but simply reduced the size of the index area and resulted in more cells being identified for manual processing rather than autoprocessing. With substantially relaxed thresholds, the index no longer tracked the AT survey walleye pollock biomass. No matter what thresholds were used, autoprocessed backscatter data alone were not able to capture the pattern of variability in 1999–2004 AT survey walleye pollock biomass. Thus I_{UDB}, calculated using only autoprocessed data, was negatively correlated with the AT survey time series ($r^2 = 0.32$, Fig. 3), and relative estimation error bars did not overlap in 2 of 4 years.

BT survey index (I_{BT}, 2006–2009)

During 2006–2009, with data from both BT and AT surveys available, I_{BT} was compared within and between years with results of the full AT survey. In some years, for logistical reasons, not all criteria were met for all 138 index area cells to be included in the I_{BT} computation; for example, in a few instances all acoustic data were excluded from a cell because filters removed more than 15% of the pings from data files in that cell, or a cell was not transited by a vessel. The number of cells containing valid data was 136 in 2006, 121 in 2007, 137 in 2008, and 138 in 2009 (e.g., Figs. 1*b*, 1*c*, 1*d*). To ensure comparability among years, the I_{BT} value for each year was multiplied by a scaling factor consisting of the total number of index area cells divided by the number of index area cells containing valid BT survey data in that year. The results show that I_{BT} (2006–2009) closely tracked the temporal variation in midwater walleye pollock biomass as measured by the AT survey (2006–2009, $r^2 = 1.00$; Fig. 3).

Large-scale walleye pollock spatial patterns based on either the AT or BT survey acoustic data also agreed well with one another, showing similar walleye pollock distributions across the shelf during summer (Figs. 4*a*–4*h*). Although the index

Fig. 4. Backscatter classified as walleye pollock from the bottom trawl (BT) survey index area (panels *a*, *c*, *e*, *g*) and the acoustic-trawl (AT) survey (panels *b*, *d*, *f*, *h*) in summers 2006–2009. A solid blue line indicates the 200 m depth contour. The diagonal dashed line in the upper left corner of each plot indicates the boundary between the USA and the Russian Exclusive Economic Zone.



area covers only part of the AT survey, both data sets indicated that most midwater walleye pollock were located west of 170°W in 2006–2009. As in the retrospective analysis results, over 80% of the total AT survey midwater walleye pollock biomass occurred in the index area. These observations corroborate the retrospective analysis findings that the index area is a reasonable indicator of both the distribution and the abundance of the entire EBS midwater walleye pollock stock. The I_{AT} CG was close to and west of the CG of the AT survey in each year (Fig. 5). I_{AT} CG was within 46.0 km of the AT survey backscatter on average, ranging from 28.9 km in 1999 to 74.3 km in 2004. Likewise, the CG of I_{BT} (2006–2009) was close to the AT survey CG; it was to the west in 2006, 2008, and 2009, but it was to the east in 2007. The I_{BT} CG was within 38.6 km of the CG of the AT survey backscatter on average, ranging between 2.2 km in 2009 and 73.2 km in 2007 (Fig. 5). The global index of collocation (Fig. 6) for I_{AT} and AT survey indicated nearly complete overlap (I_g = 1.0), while the local index of collocation showed somewhat less fine-scale coherence (I_l = 0.9). On the large scale, I_g indicated that I_{BT} and the AT survey backscatter overlapped in all 4 years (>0.99). However, I_l indicated that on the fine scale there was much less spatial coherence (mean I_l = 0.5; Fig. 6).

Discussion

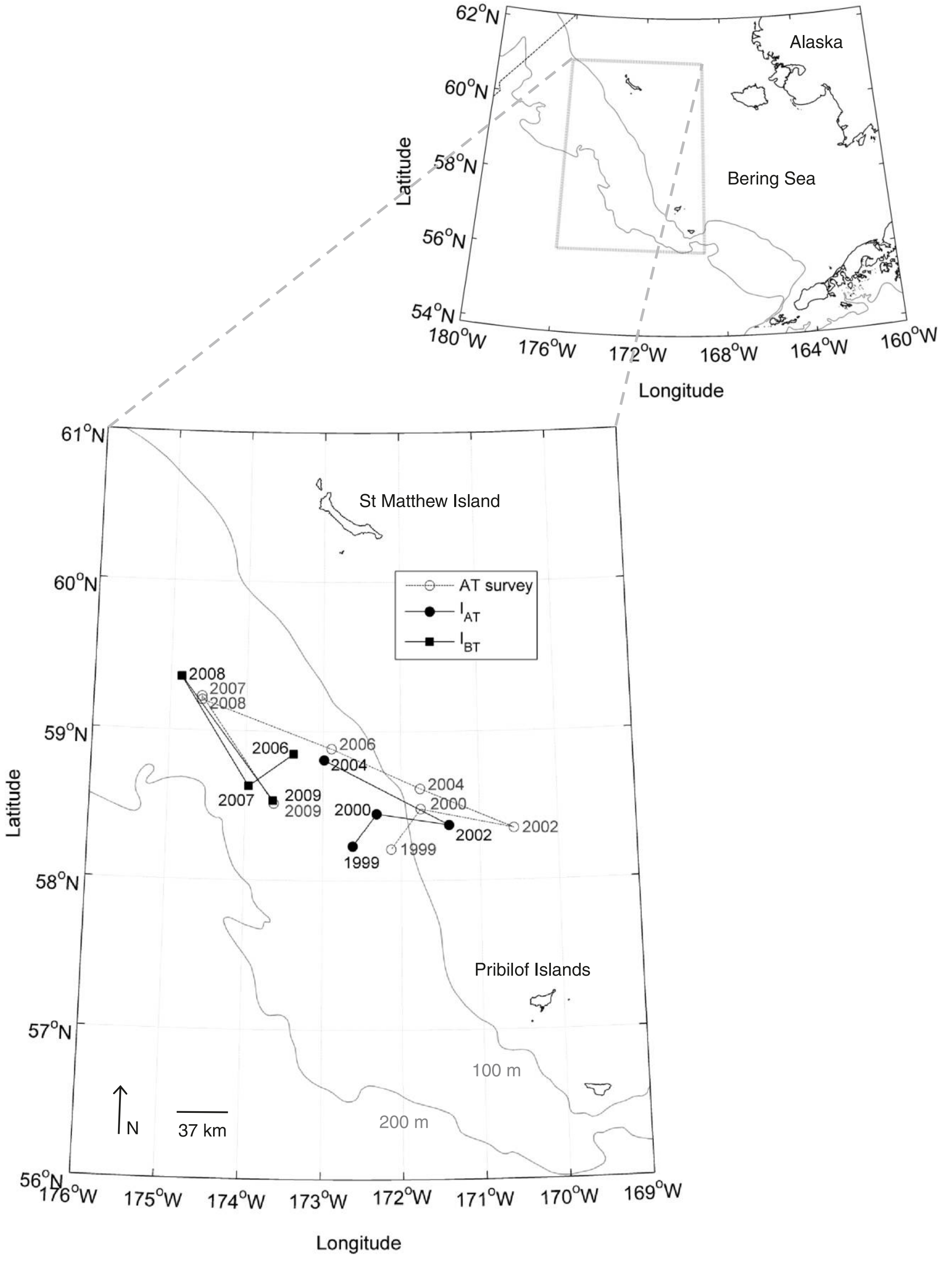
The new annual BT index (I_{BT}; 2006–2009) closely tracked the results of the AT survey and thus can provide information on midwater walleye pollock abundance at relatively little cost when the AT survey is not conducted. The retrospective index (I_{AT}; 1999–2004) demonstrated that analyzing a region smaller than the entire AT survey area to track walleye pollock abundance was feasible and allowed for use of an automated analysis procedure to save time and effort during data analysis.

Spatial analyses of I_{AT} and the AT survey backscatter provided context for subsequent comparison of the I_{BT} and AT survey backscatter. Both sets of comparisons showed broad overlap at a large scale. The I_{AT} and AT survey were expected to be very similar because they came from the same data set. The main differences between the two, namely the westward displacement of the I_{AT} CGs and fine-scale differences indicated by local collocation index values < 1, stem from using a subset of the AT survey data to compute I_{AT}. Proportionally more index area cells were in the western portion of the AT survey area, and the backscatter data were attributed to walleye pollock differently in I_{AT} than in the AT survey. The much lower fine-scale spatial coherence between I_{BT} and the AT survey than between I_{AT} and the AT survey is not surprising because the BT survey and the AT survey are different data sets; they sample the grid cells of the index region at different times while seasonal movement and migration of walleye pollock are occurring over the course of the summer (Kotwicki et al. 2005). In addition, while the AT survey progresses from east to west along the north–south survey transects, the order in which the BT survey vessel(s) move among the grid cells changes from year to year, which might lead to additional interannual sampling variability. Thus the weaker fine-scale coherence between I_{BT} and the AT survey may simply indicate localized fish movement within the surveyed area and increased sampling variability in the BT survey data.

The large-scale spatial agreement between the walleye pollock distributions estimated by the AT survey and the new I_{BT} suggests that the index provides a way of monitoring not only annual abundance, but also shelf-wide distribution of midwater walleye pollock. For example, the distribution of walleye pollock backscatter in the I_{BT} shows that most midwater walleye pollock were located west of 170°W in 2006–2009, an observation consistent with the results of AT surveys, BT survey trawl data, and reports from the commercial fishery during those years (Honkalehto et al. 2010; Lauth 2010; Ianelli et al. 2009). Knowledge of the large-scale spatial distribution of walleye pollock has both ecological and commercial importance. This information together with observations of physical oceanographic conditions, distribution of prey resources, and age structure of the stock can potentially be used to better understand the mechanisms that determine walleye pollock distribution patterns (Kotwicki et al. 2005; Mueter et al. 2006). These distribution patterns can be used in economic models to forecast economic impacts on the fishery (e.g., Haynie and Layton 2010). For example, fishing vessels traveled substantially greater distances from port during 2007 and 2008 and incurred greater transportation costs to find sufficient concentrations of walleye pollock (Ianelli et al. 2008).

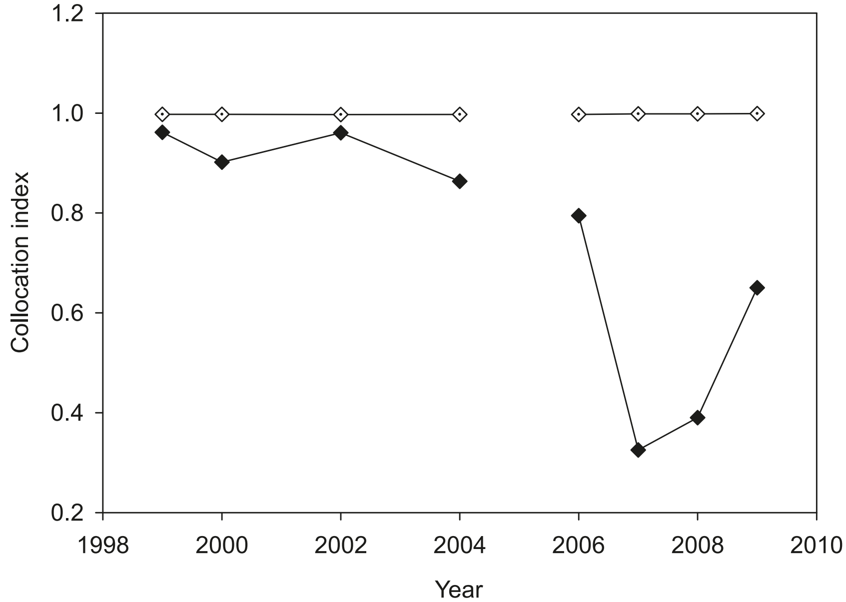
The use of commercial vessels as platforms to collect acoustic data to assess commercial fish species is becoming more common (International Council for the Exploration of the Sea 2007), especially in lieu of using scientific vessels when competition for ship time is intense among programs and operational costs are high. As with dedicated AT surveys, acoustic data from commercial fishing vessel platforms should be from an unbiased sampling design using calibrated, scientific-quality echo sounders that are operated under favorable conditions (e.g., minimal noise interference). These data can then be used to reliably estimate fish distribution and abundance. In a number of these studies (e.g., Claytor and Allard 2001; Melvin et al. 2002), the commercial vessels collect acoustic data while conducting fishing operations and are unable (or do not attempt) to conduct comprehensive surveys or sample along regularly spaced transects, which are favored for the design of acoustic surveys of fish populations (Simmonds and MacLennan 2005). The present study took advantage of the regular sampling grid of the BT survey trawl stations. Despite design differences between the two surveys, the 2006–2009 I_{BT} showed similar temporal and spatial patterns of walleye pollock distribution, and similar sampling variance estimates, to the AT survey. The calibration variability among fishing vessel acoustics systems was not dramatically different than those of the research vessels. This was also the case in earlier work involving calibration comparisons between commercial and research vessels (Claytor and Allard 2001). Acoustic interference was eliminated in the present study by turning off or synchronizing other acoustic equipment on board the fishing vessels. Since the AT and BT surveys occur in summer months when the Bering Sea typically has fewer and smaller storms compared with winter conditions, weather-generated data collection problems such as bubble sweepdown (Ona and Traynor 1990) that might be severe with hull-mounted transducers were infrequent enough

Fig. 5. Center of gravity estimates for walleye pollock backscatter from the indices I_{AT} (1999–2004) and I_{BT} (2006–2009) (solid black lines), and the acoustic-trawl (AT) survey (dashed gray line) for 1999–2009. The 200 and 100 m isobaths are shown by solid gray lines.



to be successfully detected and addressed during postprocessing. This study did not investigate or control for differences in fish density estimates caused by potential differences in fish reaction between vessels. Two vessel comparison of daytime acoustic measurements of Bering Sea walleye pollock density during the AT survey between a noise-reduced and a traditional research vessel found little difference in walleye pollock behavior that affected density estimates (De Robertis et al. 2008, 2010). Finally, although noise-reduced, special-purpose acoustic research vessels may be preferable for dedi-

Fig. 6. Global (I_g, open diamond with dot) and local (I_l, solid diamond) indices of collocation estimates between acoustic-trawl (AT) survey walleye pollock s_A and I_{AT} index s_A (1999–2004), and AT survey walleye pollock s_A and I_{BT} index s_A (2006–2009).



cated acoustic surveys of fish (International Council for the Exploration of the Sea 2007; De Robertis and Wilson 2010), the good spatial and temporal agreement demonstrated here between I_{BT} and the AT survey results suggests that data collected by these commercial fishing vessels were adequate for constructing a summer index of walleye pollock abundance and distribution.

A standard acoustic survey of fish abundance is assumed to detect all or some known fraction of the stock of interest; this fraction may be estimated by stock assessment models that use the survey results (Simmonds and MacLennan 2005; Ianelli et al. 2008). For a new index survey where only a portion of the stock of interest is detected, the trend in abundance for the index must accurately represent changes in the entire stock. Ressler et al. (2009) argued that a new index of widow rockfish (*Sebastes entomelas*) abundance based on acoustic data collected by fishing vessels would meet this standard based on the historical fish distribution inferred from commercial catches and habitat preferences of that species. The index for walleye pollock presented here, based on 4 years of BT survey data, was consistent with the trend in the abundance and spatial distribution of the midwater walleye pollock stock based on the dedicated AT survey. The study is unique because it not only provides an annual abundance index, but also allows evaluation of the index performance against an independent estimate of midwater walleye pollock abundance, namely the biennial AT survey results. Although some other studies involving collection of acoustic data from fishing vessels provide abundance indices (Stanley et al. 2000; Honkalehto and Ryan 2003; O'Driscoll and Macaulay 2005), none has built-in, research vessel survey comparisons for evaluation of index performance.

Acoustic-based estimates of abundance are critically important in fisheries management, as illustrated by their direct influence on quota recommendations (e.g., Ianelli et al. 2009). The costs of collecting, processing, and using results based on acoustic data from these fishing vessels are minor compared with the costs of conducting a dedicated AT survey. Although the precision of the acoustic data collected from the commercial vessels during the BT survey may be lower than that obtained with more costly dedicated efforts, the opportunity to collect and analyze these data to estimate the index presented here will undoubtedly provide better information for advice on critical near-term fisheries management actions.

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References

Barbeaux, S.J., Dorn, M., Ianelli, J., and Horne, J. 2005. Visualizing Alaska pollock (*Theragra chalcogramma*) aggregation dynamics. ICES CM U-01.

Bez, N., and Rivoirard, J. 2000. Indices of collocation between populations. *In* Report of a workshop on the use of continuous underway fish egg sampler (CUFES) for mapping spawning habitats of pelagic fish. *Edited by* D.M. Checkley, Jr., J.R. Hunter, L. Motos, and C.D. van der Lingen. GLOBEC Rep. 14. pp. 48–52.

Bez, N., Rivoirard, J., and Guiblin, P.H. 1997. Covariogram and related tools for structural analyses of fish survey data. *In* Geostatistics Wollongong '96, Vol. 2. *Edited by* E.Y. Baafi and N.A. Schofield. Kluwer Academic Publishers, Dordrecht, the Netherlands. pp. 1316–1327.

Claytor, R.R., and Allard, J. 2001. Properties of abundance indices obtained from acoustic data collected by inshore herring gillnet boats. Can. J. Fish. Aquat. Sci. **58**(12): 2502–2512. doi:10.1139/cjfas-58-12-2502.

Cox, M.J., MacKenzie, M.L., Watkins, J.L., and Brierley, A.S. 2006. The effect of missing acoustic observations (dropped pings) on mean area density estimates of Antarctic krill (*Euphausia superba*). ICES CM /I:16.

De Robertis, A., and Wilson, C.D. 2006. Walleye pollock respond to trawling vessels. ICES J. Mar. Sci. **63**(3): 514–522. doi:10.1016/j.icesjms.2005.08.014.

De Robertis, A., and Wilson, C.D. 2010. Silent ships sometimes do encounter more fish. 2. Concurrent echosounder observations from a freedrifting buoy and vessels. ICES J. Mar. Sci. **67**(5): 996–1003. doi:10.1093/icesjms/fsp301.

De Robertis, A., Hjellvik, V., Williamson, N.J., and Wilson, C.D. 2008. Silent ships do not always encounter more fish: comparison of acoustic backscatter recorded by a noise-reduced and a conventional research vessel. ICES J. Mar. Sci. **65**(4): 623–635. doi:10.1093/icesjms/fsn025.

De Robertis, A., Wilson, C.D., Williamson, N.J., Guttormsen, M.A., and Stienessen, S. 2010. Silent ships sometimes do encounter more fish. 1. Vessel comparisons during winter pollock surveys. ICES J. Mar. Sci. **67**(5): 985–995. doi:10.1093/icesjms/fsp299.

Food and Agriculture Organization of the United Nations. 2009. The state of world fisheries and aquaculture 2008, part 1. World review of fisheries and aquaculture. FAO Fisheries and Aquaculture Department, Rome, Italy. Available from http://www.fao.org/docrep/011/i0250e/i0250e00.htm.

Foote, K.G., Knudsen, H.P., Vestnes, G., MacLennan, D.N., and Simmonds, E.J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep. No. 144.

Haynie, A.C., and Layton, D.F. 2010. An expected profit model for monetizing fishing location choices. J. Environ. Econ. Manage. **59**(2): 165–176. doi:10.1016/j.jeem.2009.11.001.

Honkalehto, T., and Ryan, T.E. 2003. Analysis of industry acoustic observations of orange roughy (*Hoplostethus atlanticus*) spawning aggregations on the Cascade Plateau off southeastern Tasmania in June and July 2003. CSIRO report to the Deepwater Assessment Group, Hobart, Tasmania, Australia. Available from http://www.cmar.csiro.au/e-print/open/ryante_2003.pdf.

Honkalehto, T., Patton, W., de Blois, S., and Williamson, N. 2002. Echo integration-trawl survey results for walleye pollock (*Theragra chalcogramma*) on the Bering Sea shelf and slope during summer 1999. US Dept. Commer. NOAA Tech. Memo. NMFS-AFSC-125. Available from http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-125.pdf.

Honkalehto, T., Williamson, N., Jones, D., McCarthy, A., and McKelvey, D. 2008. Results of the echo integration-trawl survey of walleye pollock (*Theragra chalcogramma*) on the U.S., and Russian Bering Sea shelf in June and July 2007. US Dep. Commer. NOAA Tech. Memo. NMFS-AFSC-190. Available from http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-190.pdf.

Honkalehto, T., McCarthy, A., Ressler, P., Stienessen, S., and Jones, D. 2010. Results of the acoustic-trawl survey of walleye pollock (*Theragra chalcogramma*) on the U.S., and Russian Bering Sea shelf in June–August 2009 (DY0909). AFSC Processed Rep. 2010-03. Alaska Fish. Sci. Cent. NOAA, Natl. Mar. Fish. Serv. Available from http://www.afsc.noaa.gov/Publications/ProcRpt/PR2010-03.pdf.

Ianelli, J.N., Barbeaux, S., Honkalehto, T., Kotwicki, S., Aydin, K., and Williamson, N. 2008. Assessment of the walleye pollock stock in the Eastern Bering Sea. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage, Alaska. Available from http://www.afsc.noaa.gov/refm/docs/2008/EBSpollock.pdf.

Ianelli, J.N., Barbeaux, S., Honkalehto, T., Kotwicki, S., Aydin, K., and Williamson, N. 2009. Assessment of the walleye pollock stock in the Eastern Bering Sea. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea/Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage, Alaska. Available from http://www.afsc.noaa.gov/refm/docs/2009/EBSpollock.pdf.

International Council for the Exploration of the Sea. 2007. Collection of acoustic data from fishing vessels. ICES Coop. Res. Rep. No. 287.

Kotwicki, S., Buckley, T.W., Honkalehto, T., and Walters, G. 2005. Variation in the distribution of walleye pollock (*Theragra chalcogramma*) with temperature and implications for seasonal migration. Fish. Bull. **103**: 574–587.

Kotwicki, S., De Robertis, A., von Szalay, P., and Towler, R. 2009. The effect of light intensity on the availability of walleye pollock (*Theragra chalcogramma*) to bottom trawl and acoustic surveys. Can. J. Fish. Aquat. Sci. **66**(6): 983–994. doi:10.1139/F09-055.

Lauth, R.R. 2010. Results of the 2009 eastern Bering Sea continental shelf bottom trawl survey of groundfish and invertebrate resources. US Dept. Commer. NOAA Tech. Memo. NMFS-AFSC-204. Available from http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-204.pdf.

Mackinson, S., and van der Kooij, J. 2006. Perceptions of fish distribution, abundance and behaviour: Observations revealed by alternative survey strategies made by scientific and fishing vessels. Fish. Res. **81**(2–3): 306–315. doi:10.1016/j.fishres.2006.06.023.

MacLennan, D.N., Fernandes, P.G., and Dalen, J. 2002. A consistent approach to definitions and symbols in fisheries acoustics. ICES J. Mar. Sci. **59**(2): 365–369. doi:10.1006/jmsc.2001.1158.

Melvin, G.D., Li, Y., Mayer, L.A., and Clay, A. 2002. Commercial fishing vessels, automatic acoustic logging systems and 3D data visualization. ICES J. Mar. Sci. **59**(1): 179–189. doi:10.1006/jmsc.2001.1124.

Mueter, F.J., Ladd, C., Palmer, M.C., and Norcross, B.L. 2006. Bottom-up and top-down controls of walleye pollock (*Theragra chalcogramma*) on the eastern Bering Sea shelf. Prog. Oceanogr. **68**: 152–183.

O'Driscoll, R.L., and Macaulay, G. 2005. Using fish processing time to carry out acoustic surveys from commercial vessels. ICES J. Mar. Sci. **62**(2): 295–305. doi:10.1016/j.icesjms.2004.11.013.

Ona, E., and Traynor, J.J. 1990. Hull-mounted, protruding transducer for improving echo integration in bad weather. ICES CM 1990/B:31.

Pena, H. 2008. *In situ* target-strength measurements of Chilean jack mackerel (*Trachurus symmetricus murphyi*) collected with a scientific echosounder installed on a fishing vessel. ICES J. Mar. Sci. **65**(4): 594–604. doi:10.1093/icesjms/fsn043.

Petitgas, P. 1993. Geostatistics for fish stock assessments: a review and an acoustic application. ICES J. Mar. Sci. **50**(3): 285–298. doi:10.1006/jmsc.1993.1031.

Petitgas, P., Goarant, A., Masse, J., and Bourriau, P. 2009. Combining acoustic and CUFES data for the quality control of fish-stock survey estimates. ICES J. Mar. Sci. **66**(6): 1384–1390. doi:10.1093/icesjms/fsp007.

Ressler, P.H., Fleischer, G.W., Wespestad, V.G., and Harms, J. 2009. Developing a commercial-vessel-based stock assessment survey methodology for monitoring the U.S. west coast widow rockfish (*Sebastes entomelas*) stock. Fish. Res. **99**(2): 63–73. doi:10.1016/j.fishres.2009.04.008.

Rivoirard, J., Simmonds, J., Foote, K.G., Fernandez, P., and Bez, N. 2000. Geostatistics for estimating fish abundance. Blackwell Science, Ltd., Oxford, UK.

Shen, H., Dorn, M.W., Wespestad, V., and Quinn, T.J. 2009. Schooling pattern of eastern Bering Sea walleye pollock and its effect on fishing behavior. ICES J. Mar. Sci. **66**(6): 1284–1288. doi:10.1093/icesjms/fsp071.

Simmonds, J., and MacLennan, D. 2005. Fisheries acoustics: theory and practice. Blackwell Science, Ltd., Oxford, UK.

Stanley, R.D., Keiser, R., Cooke, K., Surrey, A.M., and Mose, B. 2000. Estimation of a widow rockfish (*Sebastes entomelas)* shoal off British Columbia, Canada, as a joint exercise between stock assessment staff and the fishing industry. ICES J. Mar. Sci. **57**(4): 1035–1049. doi:10.1006/jmsc.2000.0588.

Walline, P.D. 2007. Geostatistical simulations of eastern Bering Sea walleye pollock spatial distributions, to estimate sampling precision. ICES J. Mar. Sci. **64**(3): 559–569. doi:10.1093/icesjms/fsl045.

Woillez, M., Poulard, J.-C., Rivoirard, J., Petitgas, P., and Bez, N. 2007. Indices for capturing spatial patterns and their evolution in time, with application to European hake (*Merluccius merluccius*) in the Bay of Biscay. ICES J. Mar. Sci. **64**(3): 537–550. doi:10.1093/icesjms/fsm025.

Woillez, M., Rivoirard, J., and Petitgas, P. 2009. Notes on survey-based spatial indicators for monitoring fish populations. Aquat. Living Resour. **22**(2): 155–164. doi:10.1051/alr/2009017.

Wyeth, M.R., Stanley, R.D., Kieser, R., and Cooke, K. 2000. Use and calibration of a quantitative acoustic system on a commercial fishing vessel. Can. Tech. Rep. Fish. Aquat. Sci. 2324.

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2. VM Trenkel, PH Ressler, M Jech, M Giannoulaki, C Taylor. 2011. Underwater acoustics for ecosystem-based management: state of the science and proposals for ecosystem indicators. *Marine Ecology Progress Series* **442**, 285-301. [CrossRef]